VERY HIGH-ENERGY COSMIC RAYS

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Recently, Linsley and Scarsi[1] have shown that present evidence indicates that the primary particles of total energy $\geq 10^{17}$ eV are nearly all protons. They further state that the heavy nuclei are less abundant than at lower energies, and may be completely absent. In a companion paper, Linsley[2] suggests that one possible explanation of this feature is that the cosmic rays of lower energy are of galactic origin, those above about 5×10^{16} eV are of metagalactic origin, and at about 10^{16} eV/nucleus the two sources make an approximately equal contribution. The intent of this Letter is to show that there is another possible interpretation, which is based on the proposition that spiral-arm segments in the galaxy may be an important controlling feature. This hypothesis can also account for the other principal known features of low- and high-energy cosmic rays.

Peters[3] has already discussed some of the important features of the cosmic radiation which can be explained by considering the effect of the spiral arms. To summarize the basic ideas of this model, omitting the refinements, the particles, after being accelerated in the supernovae, travel along a spiral arm until the particles reach the end of the arm, or the arm segment, and then enter into the galactic halo. Peters shows that the cosmic rays formed in supernovae could pass through only a few g/cm^2 of interstellar material before leaving the arm segment, in agreement with the amount of matter traversed as deduced from the relative abundance of the light nuclei ($3 \leq$ nuclear charge ≤ 5) in cosmic rays. He further notes that it may be reasonable to assume that as the particles reach the end of the arm segment they diffuse into the halo, where their average lifetime could be quite large, perhaps approaching half the age of the galaxy. He then points out that since they pass through a relatively large amount of material there will be a decrease in the number of complex nuclei due to fragmentation.

A look will now be taken at the further implications of this model. Because of the finite size of the spiral-arm segment and the strength of the field therein, there must be an upper limit to the rigidity of a particle which can be held easily in a spiral-arm segment. If a radius of curvature which is one-hundredth that of the estimated diameter of a spiral-arm segment is chosen as an upper limit for particles which should be held fairly easily in the galactic arm, the corresponding rigidity is given by

$$R_{\text{limit}} = 300\,aH = (300)(9\times10^{18})(6\times10^{-6}), \tag{1}$$

$$R_{\text{limit}} = 1.5\times10^{16}\text{ eV}; \tag{2}$$

where R is the rigidity in eV, a is the radius of curvature in cm, and H is the field strength in gauss.

Particles with rigidities above about this value will escape from the spiral arm relatively easily and subsequently pass through them relatively easily. If the average amount of material through which they pass is calculated on the basis of the assumption that the amount of time they spend in the galactic disk and the halo is proportional to their relative volume, the following expression is obtained:

$$\bar{\rho} = \left[\frac{V(\text{disk})}{V(\text{disk})+V(\text{halo})}\right]\rho(\text{disk}) + \left[\frac{V(\text{halo})}{V(\text{disk})+V(\text{halo})}\right]\rho(\text{halo}). \tag{3}$$

ρ(disk) and ρ(halo) are assumed to be 10^{-24} and 10^{-26} g/cm^3, respectively.[4,5] V(halo) and V(disk) are calculated as follows:

$$V(\text{halo}) = (4/3)\pi(4.5\times10^{22})^3 = 4\times10^{68}\text{ cm}^3, \tag{4}$$

$$V(\text{disk}) = \pi(4.5\times10^{22})^2(9\times10^{20}) = 6\times10^{66}\text{ cm}^3. \tag{5}$$

From (3), (4), and (5),

$$\bar{\rho} = 2.5\times10^{-26}\text{ g/cm}^3. \tag{6}$$

The total amount of material through which these ultrahigh-rigidity particles have passed in a period of time equal to half the estimated age of the galaxy[5] is then given by

$$(2.5\times10^{-26}\text{ g/cm}^3)(3\times10^{10}\text{ cm/sec})(2\times10^{17}\text{ sec}) = 150\text{ g/cm}^2. \tag{7}$$

Since this is very large compared to the mean free path of absorption for heavy nuclei, about 8 g/cm^2, and even helium nuclei, about 16 g/cm^2, high-rigidity particles should consist almost exclusively of protons. Since in terms of the cosmic-ray power-law spectrum in total energy protons, helium nuclei, and heavy nuclei are known to have nearly the same relative abundance above a given total energy at lower energies,[4] $\lesssim 10^{13}$ eV, the transition at about 10^{16}-eV rigidity corresponds to a very marked transition in composition at about 10^{16}- to 10^{17}-eV total energy if the source composition distributions continue to hold at energies above 10^{13} eV as would be expected.

At the same time, local scattering in the spiral arm probably becomes less and less important as the rigidity increases, so that as the escape rigidity from the spiral-arm segment is approached the motion of the particle would be primarily controlled by the general field parallel to the spiral arm. An anisotropy relative to the angle of the particles with respect to the axis of the spiral arm for primary heavy nuclei in the energy range from 10^{16} to 10^{17} eV/nucleus, such as the one suggested by the data of Hasegawa et al.,[6] might then be expected.

Because of the different history of the low- and very high-energy particles, a break in the energy spectrum of cosmic rays might also be expected at about 10^{16} eV. If the differential energy spectrum at the source is continuous, then the break will consist principally of a change in intensity and not spectral shape at this point with the change in intensity being determined primarily by the volume and lifetime of particles in the whole galaxy relative to those in the spiral arms. The volume of all the spiral-arm segments will be estimated as $10\pi r^2 l = 10\pi(4.5\times10^{20})^2\times(2\times10^{22}) = 1.3\times10^{65}$ cm^3, and the lifetime in the arm segment as the time necessary to travel 4 g/cm^2 in a medium of density 10^{-24} g/cm^3, namely, 4×10^6 years. Combining these numbers with the corresponding values for the halo given earlier, an intensity decrease in the differential spectrum of a factor of about two is expected, although this number is uncertain by as much as a factor of ten. A small change in the differential energy spectrum at this point in energy is consistent with the experimental data.[7]

It seems less likely that there should be such a smooth transition in the energy spectrum if the change in cosmic-ray composition at about 10^{16} to 10^{17} eV is attributed to a change from galactic to metagalactic origin. There must, of course, be some rigidity above which particles cannot be held easily in the galaxy, but it could reasonably be expected to be about two orders of magnitude larger than that necessary to hold a particle in an arm segment. This higher rigidity, which would then be of the order of 10^{18}- to 10^{19}-eV rigidity, will correspond to the transition from galactic to metagalactic particles. Another change in the differential energy spectrum might then be expected at this point.

The model considered here leads to a change in composition and a small change in the energy spectrum at about the same energy, estimated to be about 10^{16} to 10^{17} eV, with the change in composition occurring about a factor of two to ten higher in total energy. In addition, a possible heavy anisotropy relative to the spiral-arm segment at these energies can be explained. Finally, another and probably more significant change in the differential energy spectrum is expected at about 10^{19}-eV total energy.

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